Shallow Water Propagation

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LONG-TERM GOALS

Develop methods for deterministic and stochastic propagation calculations in complex shallow water environments, determine their capabilities and accuracy, and apply them for modeling data and understanding mechanisms.

OBJECTIVES

(A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate realistic bathymetric, topographic, and geoacoustic variations.

(B) Analyze and interpret acoustic data, quantify effects of random environmental and experimental variability, and compare predictions of field statistics for intensity and coherence.

APPROACH

(A) Develop efficient and accurate parabolic equation (PE) techniques for applications involving heterogeneous sediments. Treat range dependence and sediment layering by coordinate rotation and single scattering methods.   Benchmark results using data and specialized calculations.

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14. ABSTRACT

Develop methods for deterministic and stochastic propagation calculations in complex shallow water environments, determine their capabilities and accuracy, and apply them for modeling data and understanding mechanisms.

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(B) Construct representations for ocean environmental and geoacoustic variability using data and parametric models. Perform acoustic field calculations with PE, normal mode, and approximation methods. Use data analysis and computational results to assess propagation mechanisms.

Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. Allan Pierce (BU), Dr. James Lynch (WHOI), and Dr. Timothy Duda (WHOI) for data analysis and theoretical interpretations.

WORK COMPLETED

(A) A significant new capability is provided by the first propagation method, based on a combination of a coordinate rotation technique and a single-scattering approximation, which efficiently and accurately handles ocean seismo-acoustic problems with range dependent bathymetry and variable thickness sediment layers [1]. An extension is constructed for elastic media with topographic variations that arise in coastal and beach problems [2], for which the evolution of Scholte waves into Rayleigh waves can occur. Accuracy benchmarks for the new procedure demonstrate its improved performance over other methods, including one based on a coordinate mapping [3] that is valid for relatively large variations in bathymetry and interface depths and small rates of slope changes. Additional results show the accuracy of the single-scattering component for problems with large changes in shear and compressional sound speeds, demonstrate its connection to the widely used approach of approximate energy conservation, and describe appropriate choices for computational parameters [4]. This work expands research [5] that indicated the advantage of particular parameter choices and suggested the importance of parameter selection rules. Calculations from the new method produce excellent and unprecedented agreement with high fidelity data from range dependent propagation over an elastic slab in a laboratory tank [6]. The continuation of this experimental series uses an elastic slab with variable bottom slope, and even for this more challenging environment our propagation method provides excellent comparisons with data [7]. Increased efficiency for parabolic equation calculations at frequencies above 1 kHz is obtained for weakly varying environments [8] by combining split-step Padé and Fourier algorithms. Computations of vector intensity and acoustic particle velocity can be calculated efficiently by PE methods [9], and new examples provide useful information and insight on how these fields depend on environmental and acoustic parameters.

(B) Nonlinear frequency dependence of sediment attenuation and downward refraction of water sound speed profiles combine to produce significant sensitivity in the frequency dependence of modal attenuation coefficients [10], which are qualitatively distinct from those for Pekeris waveguides. Coefficients obtained from our approach are compared with previous estimates determined from Gulf of Mexico data [11], and a subset of measured sound speed profiles is identified for which the agreement is very good. The frequency dependence of modal attenuation coefficients is shown to be related to that of the overall (effective) attenuation for transmission loss mainly through dependence on the water sound speed profile [12]. Analysis of data from two earlier New Jersey shelf experiments near the SW06 site shows [13] that the frequency power-law exponent of the upper sediment attenuation is approximately 1.85, and that profiles of attenuation, water sound speed, and bathymetry control the accuracy of this value. Additional results [14] demonstrate that although range dependence may influence the exponent, in the New Jersey region the results are robust with respect to observed environmental variability. Nonlinear frequency dependence in sediment attenuation must be included to obtain close agreement [15] between calculations of broadband intensity variations that arise from geoacoustic uncertainties and data from an

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experiment at the New Jersey AGS location. In order to improve predictions of acoustic effects from nonlinear internal waves, feature parameters are extracted from satellite SAR images [16], and estimates are validated by comparisons with results from ground truth measurements at SW06 moorings. Acoustic modes interacting adiabatically at small incident angles with waveguides formed by nonlinear internal waves will produce interference patterns, which are modeled effectively by a horizontal Lloyd mirror [17]. Full three-dimensional propagation computations demonstrate that horizontal mode coupling may arise from multiple interacting nonlinear internal waves [18], depending on wave amplitudes, relative orientations, and coherence lengths. To determine dependence on environmental parameters and frequency conveniently, perturbation approximations are constructed [19] for mode shapes and wave numbers for a class of downward refracting sound speed profiles. These results are extended by developing two other asymptotic modal approximations [20], which are valid for complementary sets of parameter values and consequently are useful together for applications. Specifically, we examine modal attenuation coefficients [21], on which the influence of sound speed gradients at different locations in the water column is found in terms of environmental parameters.

RESULTS (from two selected investigations)

(A) An essential capability for ocean acoustic data analysis and applications is accurate and efficient propagation calculations in shallow water waveguides that involve range dependent elastic sediments. Sediment elasticity is important because transferring energy between compressional and shear modes may significantly influence the overall intensity field. In addition, effective treatment of elasticity is the necessary precursor for handling poro-elastic and other complex sediments. The physical and computational challenge, which has delayed progress for decades, is that the spectral distribution of energy is much broader in wave number space than for fluid sediments. Our state of the art PE method has evolved from a series of steps: formulating equations with non-standard dependent variables; applying coordinate rotations at ranges where bathymetry slope changes occur; using single-scattering corrections at stair-step approximations of changes in sediment interfaces and volume parameters [1]; and efficient iteration procedures for realistic elastic parameter and slope changes [4]. Benchmarking provides critical validation throughout the development, including unusually successful agreement [6], [7] with high quality data obtained from a series of tests using elastic slabs in an NRL laboratory tank. In addition the capabilities of the method continue to expand, one example being the treatment of propagation into and up a sloping beach [2]. An environment motivated by the topography and stratigraphy on the Southern California coast is illustrated in *Figure 1*. The upper panel shows compressional energy at 150 Hz propagating in both sediment layers, up the beach beyond 1.8 km, and with modal cutoff in the sediment. The influence of topography on the loss field is due to the potential for propagation into the beach, without which the energy would be lost to modal cutoff. The middle panel shows very good agreement between results from the PE and a full field finite-element calculation. The bottom panel shows inadequate agreement between results for the full field and the only other PE method capable of handling beach propagation [3], because its validity limits are exceeded by the environmental variability in this problem. We conclude from these and other results that our new propagation method provides necessary capabilities for efficient and accurate calculations in shallow water waveguides with range variations in bathymetry, topography, and elastic sediment structure and layering.
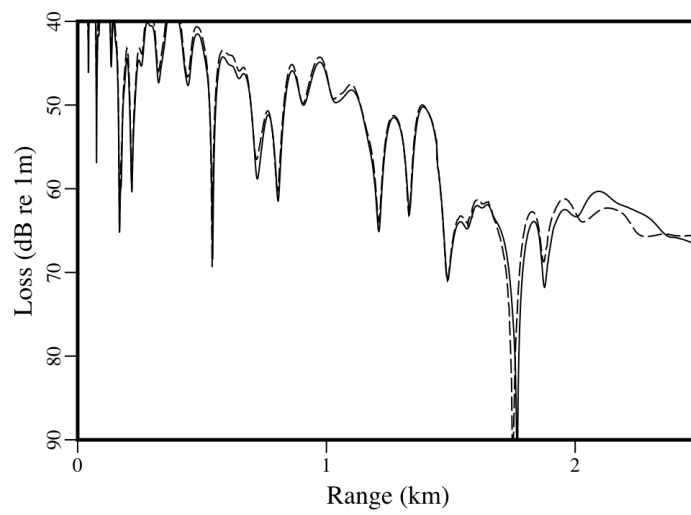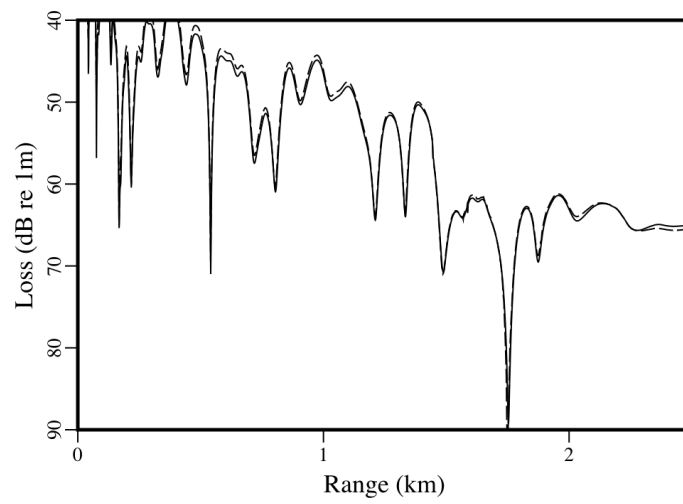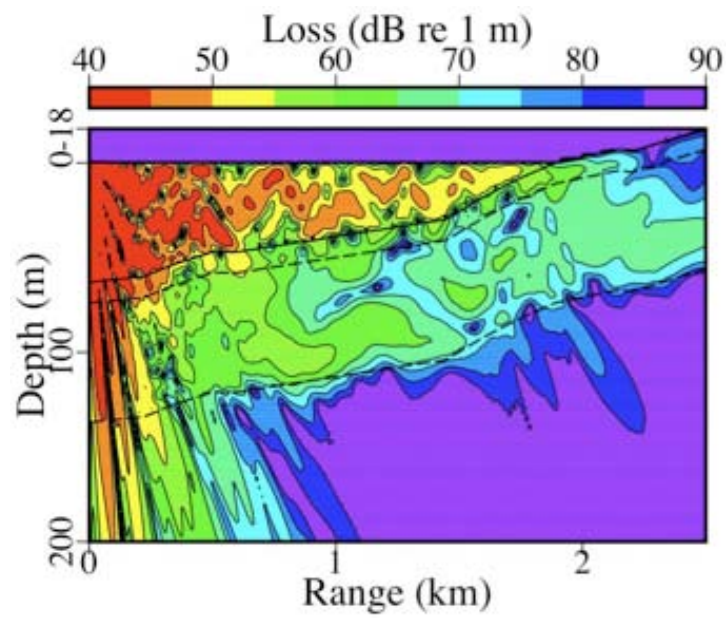
(B) Propagation predictability for low to medium frequencies remains a fundamental and relevant problem in many shallow water waveguides. Of particular interest are the relatively common and important regions with sandy-silty sediments and relatively slow bathymetric and water column variability. For such environments [11], [13], an often useful approximation for the behavior of the full intensity field may be found from the propagating waveguide modes. In this case the modal attenuation coefficients control the decay rates of individual modes and consequently of intensity. We focus on the dependence of the coefficients on environmental parameters and frequency, the latter being essential for treatment of pulse and broadband sources. One approach for determining the coefficients shows that they are functions of the frequency behavior of the sediment attenuation, sediment sound speed profile, horizontal wavenumber, and mode shape. The influence of the last factor is the least transparent [10]. For example, *Figure 2* contains results for a model environment motivated by the New Jersey shelf in the general vicinity of SW06. The sediment consists of two isospeed layers, the upper having a quadratic frequency dependence of attenuation in accord with Biot theory. The modal attenuation coefficient results do not change significantly if realistic depth-dependent sediment sound speed profiles are used instead. In contrast the water sound speed, represented in the upper left panel by one linear and three thermocline profiles, strongly influences the coefficients through changes in the mode shapes. For a Pekeris problem with isospeed water, the modal attenuation coefficients for large frequency are known to have a frequency power-law behavior with exponent N = - 1.0. The Pekeris model differs strongly from the cyan and yellow profiles, which both have overall sound speed changes of 45 m/s and sharp gradients in the upper water column. Nonetheless in the right panel, the coefficient curves corresponding to these two thermocline profiles are close to the Pekeris result and have essentially the same value of N = - 0.9. However, the magenta profile, with weaker gradient and deeper thermocline, has a qualitatively different coefficient curve with exponent N = - 0.2. The corresponding curve for the linear profile differs sharply, with attenuation increasing above about 100 Hz with exponent N = 1.0. We conclude from these and related calculations that the modal attenuation coefficients over a broad mid-frequency band depend strongly on the sound speed profile near the bottom of the water column, including both the gradient and the depth extent of the lower isospeed layer.
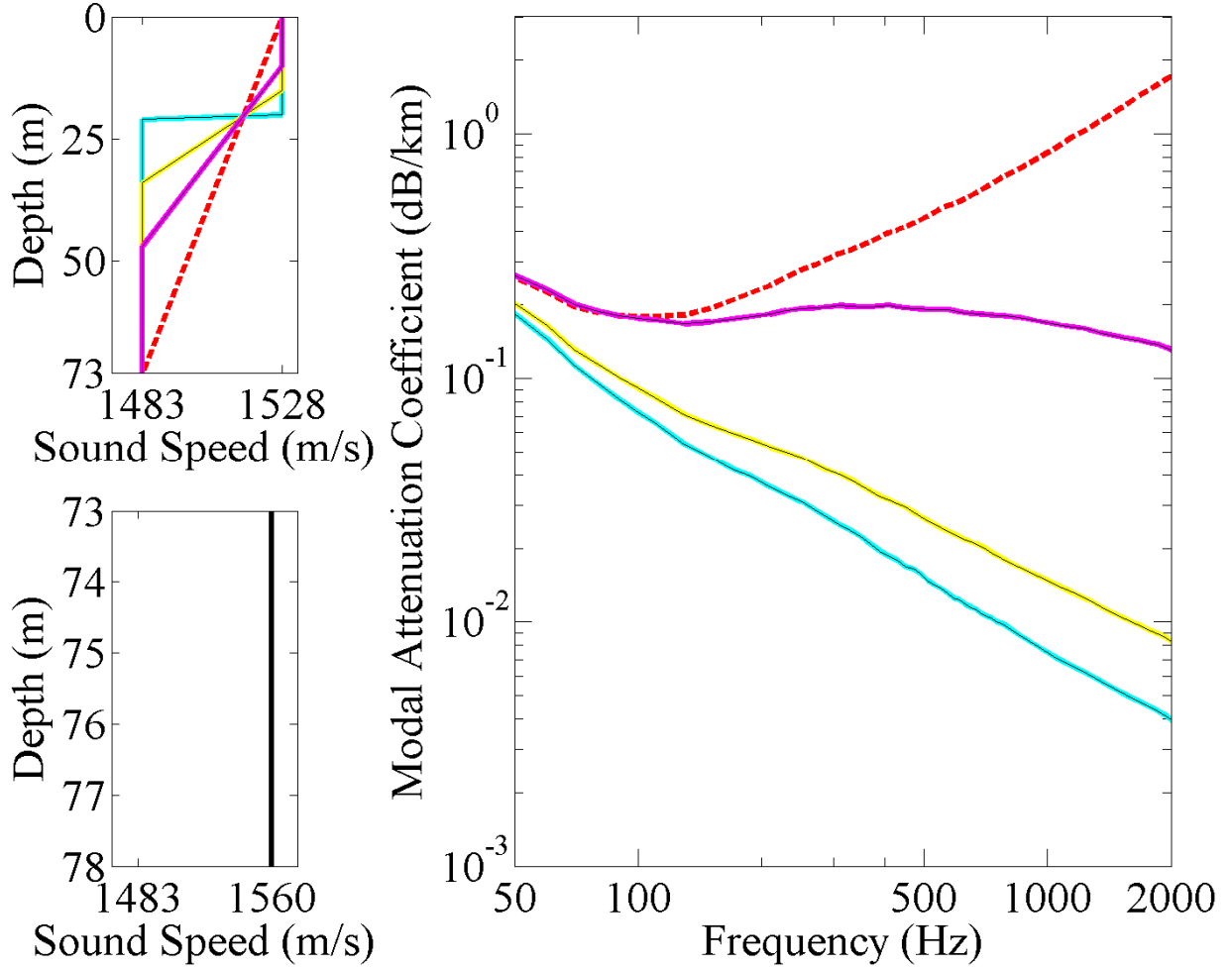
Figure 2. ***The frequency dependence of modal attenuation coefficients depends mainly on water sound speed profiles in ocean waveguides with sandy-silty sediments and weak range dependence. Upper left panel: Three piecewise-linear thermocline sound speed profiles, each having isospeed segments in the upper and lower water column with values 1528 and 1483 m/sec. The cyan, yellow, and magenta profiles have linear gradients over regions of thickness 1, 19, and 37 m. The dashed red line is a linear profile over the full 73 m water depth. Lower left panel: Sound speed of 1560 m/s in the upper sediment layer, with thickness 5 m and attenuation which is quadratic in frequency. The lower layer is a basement with sound speed 1740 m/s and attenuation which is linear in frequency. Right panel: Log-log plot of modal attenuation coefficients for mode 1, ranging from 0.001 to 1.0 dB/km, versus frequency from 10 to 2000 Hz corresponding to the four water sound speed profiles. The cyan curve decreases steadily and at large frequencies has frequency power-law exponent N of about - 0.9; the yellow curve is similar, with slightly higher attenuation; the magenta curve has decreasing attenuation to about 150 Hz, then increasing slightly to about 400 Hz, and finally decreasing for large frequencies with N = - 0.2; the red curve decreases until about 100 Hz and then steadily increases with N = 1.0. The behavior of modal attenuation coefficients for middle frequencies depends strongly on characteristics of the sound speed profile near the bottom of the water column.***

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IMPACT/APPLICATIONS

New or enhanced capabilities for handling physical properties of shallow water sediments, including layering, elasticity, porosity, and anisotropy, are provided for propagation predictions. Range dependent variability from bathymetry, topography, and sediment layer interfaces can be treated accurately in propagation calculations. Intensity attenuation and coherence statistics that result from environmental fluctuations and experimental variability can be found efficiently. Data analyses and comparisons permit specifying, for experimental and application purposes, the relative significance of key physical mechanisms: linear versus nonlinear frequency dependence of sediment attenuation, water column versus bathymetric variability, sediment heterogeneity versus homogeneity, and vertical versus horizontal mode coupling due to internal solitons and bathymetry. Results from modeling and data analyses of experiments, including several New Jersey Shelf experiments and the ACT series, are partly aimed toward improving shallow water sonar systems and predictions. New propagation model implementations, analysis tools, and data representation techniques are distributed to university, laboratory, and research and development groups.

RELATED PROJECTS

- Continuing projects with Dr. Michael Collins include completion of a monograph on state of the art advances in parabolic wave equation models and applications [22], for which principal research issues are resolved. Benchmark comparisons [23] confirm the accuracy and efficiency of recent parabolic equation calculations for range dependent elastic media and lead to implementation improvements.

- Research with Dr. William Carey and Dr. Allan Pierce examines predictability and environmental sensitivity of propagation characteristics such as coherence scales and frequency behavior of intensity attenuation. For example, transverse coherence lengths using data from the ACT III experiment in the Strait of Korea [24] show substantial horizontal variations for environments with anistotropic or heterogeneous correlation functions that may arise from internal waves.

- Investigations with Dr. James Lynch, Dr. Timothy Duda, and their colleagues focus on influences of water column variability, especially waveguides generated by nonlinear internal waves. One problem is to quantify the striking dispersion features of sound emanating from such waveguides where they terminate [25].

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PUBLICATIONS

- Published [refereed]: [1], [3], [6], [8], [13]

- Submitted [refereed]: [2], [15]

- Proceedings [non-refereed]: [19], [23]